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(71) Applicant (for all designated States except US): ICO SERVICES LIMITED [GB/GB]; Symphony House, High Street Cowley, Cowley Business Park, Uxbridge, Middlesex UB8 2AD (GB).

(72) Inventor; and
(75) Inventor/Applicant (for US only): MULLINS, Dennis, Roy [GB/GB]; 23 Kennington Palace Court, Sancroft Street, London SE11 5UL (GB).

(74) Agents: MUSKER, David, Charles et al.; R.G.C. Jenkins & Co., 26 Caxton Street, London SW1H 0RJ (GB).

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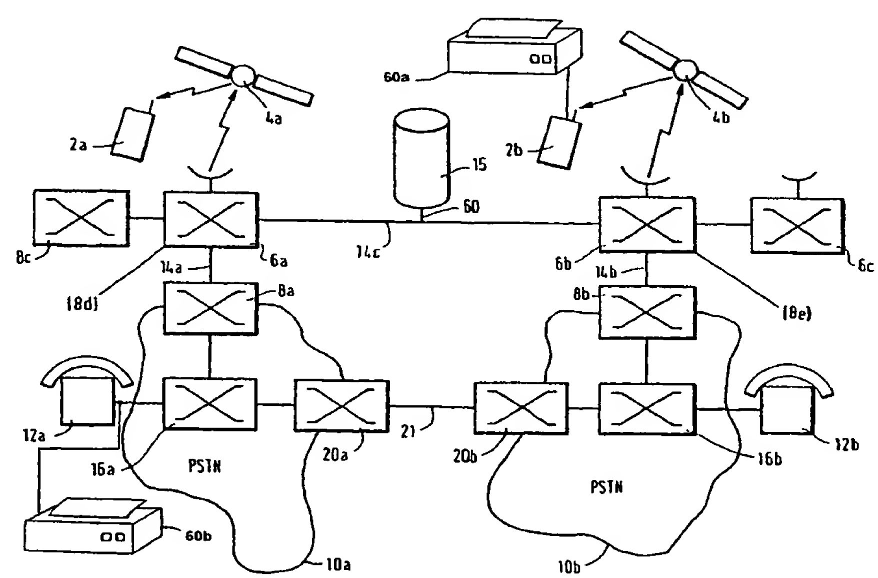

(57) **Abstract:** A satellite system comprising at least one satellite (4); at least one Earth station (6), and a plurality of user terminals (2), the satellite (4) being arranged to provide a link between each user terminal (2) and the Earth station (6), via a plurality of user terminal link beams (B1-BN) carrying communications channels, there being fewer independent said channels than the maximum number of beams which said satellite (4) can generate, said channels being reused between said beams (B1-BN); the system comprising means for directing said beams to positions determined in dependence upon the positions of said user terminals (2), and means for allocating said channels to said beams to reduce co-channel interference between said beams at said user terminals (2).

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SATELLITE COMMUNICATIONS WITH BEAMS DIRECTED TO USER POSITIONS

This invention relates to satellite communications, and particularly to multipoint satellite communications, such as mobile communications.

Satellite mobile communications systems are well known. In recent years, a number of certain systems have been proposed, including the recently launched Iridium system, and the proposed GlobalStar and ICO systems, which are intended for communications with small mobile terminals such as handsets.

One problem in such communications is to achieve sufficient link margin, for which purpose high gain antennas are used in both the user downlink and user uplink directions. To achieve this whilst covering a large area of the Earth visible to the satellite (which is necessary in order to reduce the number of satellites), an array of narrow beams are generated as disclosed in, for example, WO 95/28747. It is then also possible to re-use frequencies between non-neighbouring beams, as in terrestrial cellular communications. A regular array of beams is used, and frequencies are allocated in a repeating pattern.

In some proposals (e.g. as in EP 0575678, EP 0610789, and the proposed Odyssey system of TRW), the grid of beams is steered to centre it on anticipated hotspots such as cities, or to concentrate cover on landmasses.

In older satellite systems, for example for military use in communication with naval ships, a few separate steered beams were provided one to each ship, the ships having steered antennas. However, in such situations, the bandwidth, and gain constraints were much less onerous than in modern "cellular" satellite systems, which have many more terminals each with a lower gain antenna.

US 5754139 discloses a satellite communications system in which more beams are allocated to areas with higher anticipated demand, and there is some provision for individual beams for some users, which beams track the user position on the Earth as the satellite moves in orbit.

As use of information technology increases, there is an increasing demand for bandwidth which is, however, a scarce resource for satellite systems since they must avoid conflict with any terrestrial usages in many different countries.

The present invention is intended to provide a bandwidth-efficient satellite communications system, particularly for relatively low power mobile terminals.

This is achieved by determining user positions; providing multiple independent beams, one for each user, which are steered to ground positions based on the user positions; and selecting the beam frequencies to satisfy predetermined re-use constraints, based on the beam positions.

In a preferred embodiment, the ground positions are selected to reduce interference between beams, whilst being relatively close to the user positions to maintain gain.

Other aspects and preferred embodiments of the invention, together with corresponding advantages, will be apparent from the following description, drawings and claims.

Embodiments of the invention will now be illustrated, by way of example only, with reference to the accompanying drawings in which:

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a block diagram showing schematically the elements of a communications system embodying the present invention;

Figure 2 is a block diagram showing schematically the elements of an Earth station node forming part of the embodiment of Figure 1;

Figure 3 illustrates schematically the disposition of satellites forming part of Figure 1 in orbits around the Earth;

Figure 4 illustrates schematically the beams produced by a satellite in the embodiment of Figure 1;

Figure 5 is a cross section through a beam, showing gain against angular displacement from the antenna boresight axis;

Figure 6 is a block diagram illustrating schematically the structure of the payload of a satellite transponder;

Figure 7 shows schematically the content of a database forming part of the satellite payload of Figure 6;

Figure 8 is a flow diagram showing the operation of the satellite payload of Figure 6;

Figure 9 is a diagram illustrating the contents of a database forming part of the Earth station of Figure 2;

Figure 10 is a flow diagram showing part of the operation of the Earth station of Figure 2; and

Figure 11 (to be read with Figure 10) shows the remaining part of the operation at the Earth station in a first embodiment;

Figure 12 (corresponding to Figure 4) shows the effect of altering the beam aim point according to the process of Figure 11;

Figure 13 (comprising Figures 13a and 13b) is a flow diagram showing the operation of the Earth station according to a second embodiment of the invention; and

Figure 14 is a diagram illustrating the contents of a database forming part of the Earth station of Figure 2.

GENERAL ASPECTS OF EMBODIMENTS

Referring to Figure 1, a satellite communications network according to this embodiment comprises mobile user terminal equipment 2a, 2b (e.g.

handsets 2a and 2b); orbiting relay satellites 4a. 4b; satellite Earth station nodes 6a. 6b; satellite system gateway stations 8a. 8b; terrestrial (e.g. public switched) telecommunications networks 10a, 10b; and fixed telecommunications terminal equipment 12a, 12b.

Interconnecting the satellite system gateways 8a. 8b with the Earth station nodes 6a, 6b, and interconnecting the nodes 6a, 6b with each other, is a dedicated ground-based network comprising channels 14a, 14b, 14c. The satellites 4, Earth station nodes 6 and lines 14 make up the infrastructure of the satellite communications network, for communication with the mobile terminals 2, and accessible through the gateway stations 8.

A terminal location database station 15 (equivalent to a GSM HLR) is connected, via a signalling link 60 (e.g. within the channels 14 of the dedicated network), to the gateway station and Earth stations 6.

The PSTNs 10a. 10b comprise, typically, local exchanges 16a, 16b to which the fixed terminal equipment 12a, 12b is connected via local loops 18a, 18b; and international switching centres 20a, 20b connectable one to another via transnational links 21 (for example, satellite links or subsea optical fibre cable links). The PSTNs 10a, 10b and fixed terminal equipment 12a, 12b (e.g. telephone instruments) are well known and almost universally available today.

For voice communications, each mobile terminal apparatus is in communication with a satellite 4 via a full duplex channel (in this

embodiment) comprising a downlink channel and an uplink channel, for example (in each case) a TDMA time slot on a particular frequency allocated on initiation of a call, as disclosed in UK patent applications GB 2288913 and GB 2293725. The satellites 4 in this embodiment are non geostationary, and thus, periodically, there is handover of each user from one satellite 4 to another.

Terminal 2

The user terminals (UT's) 2a, 2b may be similar to those presently available for use with the GSM system, comprising a digital low rate coder/decoder, together with conventional microphone, loudspeaker, battery and keypad components, and a radio frequency (RF) interface and antenna suitable for satellite communications.

Each UT 2 comprises an omnidirectional antenna, i.e. an antenna having generally satisfactory communications performance at all directions above a certain minimum elevation above the horizon (such as ten degrees) so as not to require pointing or steering to a satellite.

Small satellite communications terminals are currently available (with omnidirectional antennas) for the Iridium system from Motorola Inc, and (with steered antennas) for the Inmarsat-M and mini-M systems, for example.

Terminals may be connected, as shown, to data terminal equipment 160a, 160b such as a facsimile machine or a personal computer.

Earth Station Node 6

The Earth station nodes 6 are arranged for communication with the satellites.

Each Earth station node 6 comprises, as shown in Figure 2, a conventional satellite Earth station 22 (functioning somewhat equivalently to the Base Station of a cellular system) consisting of at least one satellite tracking antenna 24 arranged to track at least one moving satellite 4, RF power amplifiers 26a for supplying a signal to the antenna 24, and 26b for receiving a signal from the antenna 24; and a control unit 28 for storing the satellite ephemera data, controlling the steering of the antenna 24, and effecting any control of the satellite 4 that may be required (by signalling via the antenna 24 to the satellite 4).

The Earth station node 6 further comprises a mobile satellite switching centre 42 comprising a network switch 44 connected to the trunk links 14 forming part of the dedicated network. It may be, for example, a commercially available mobile switching centre (MSC) of the type used in digital mobile cellular radio systems such as GSM systems.

A multiplexer 46 is arranged to receive switched calls from the switch 44 and multiplex them into a composite signal for supply to the amplifier 26 via a low bit-rate voice codec 50. Finally, the Earth station node 6 comprises a local store 48 storing details of each mobile terminal equipment 2a within the area served by the satellite 4 with which the node 6 is in communication. The local store 48 acts to fulfil the functions of a visited location register

(VLR) of a GSM system, and may be based on commercially available GSM products.

Alternatively, satellite control may be provided from a separate control station.

Other Network Elements

The gateway stations 8a, 8b comprise,. in this embodiment, commercially available mobile switch centres (MSCs) of the type used in digital mobile cellular radio systems such as GSM systems. They could alternatively comprise a part of an international or other exchange forming one of the PSTNs 10a, 10b operating under software control to interconnect the networks 10 with the satellite system trunk lines 14.

The gateway stations 8 comprise a switch arranged to interconnect incoming PSTN lines from the PSTN 10 with dedicated service lines 14 connected to one or more Earth station nodes 6.

The database station 15 comprises a digital data store which contains, for every subscriber terminal apparatus 2, a record showing the identity (e.g. the International Mobile Subscriber Identity or IMSI); the service provider station 8 with which the apparatus is registered (to enable billing and other data to be collected at a single point) and the currently active Earth station node 6 with which the apparatus 2 is in communication via the satellite 4.

Thus, in this embodiment the database station 15 acts to fulfil the functions of a home location register (HLR) of a GSM system, and may be based on commercially available GSM products.

Periodically, the Earth station nodes measure the delay and Doppler shift of communications from the terminals 2 and calculate the rough terrestrial position of the mobile terminal apparatus 2 using the differential arrival times and/or Doppler shifts in the received signal. The position is then stored in the database 48.

The Earth stations 6 are positioned dispersed about the Earth such that for any orbital position, at least one Earth station 6 is in view of a satellite 4.

Referring to Figure 3, a global coverage constellation of satellites is provided, consisting of a pair of orbital planes each inclined at 45 degrees to the equatorial plane, spaced apart by 90 degrees around the equatorial plane, each comprising ten pairs of satellites 4a, 4b, (i.e. a total of 20 operational satellites) the pairs being evenly spaced in orbit, with a phase interval of zero degrees between the planes (i.e. a 10/2/0 constellation in Walker notation) at an altitude of about 10,000 km.

Thus, neglecting blockages, a UT at any position on Earth can always have a communications path to at least one satellite 4 in orbit ("global coverage").

<u>Satellites 4</u>

The satellites 4 comprise a bus module and a payload module. The bus module comprises the elements of the satellite which are common to all satellite applications.

Specifically, the bus module comprises a propulsion system comprising thrusters for maintaining the satellite in its assigned orbital position: a power subsystem comprising, for example, a pair of solar power-wings pointed at the sun and a storage battery charged from the solar panel and discharged when the satellite is not in view of the sun; and a thermal control subsystem to dissipate heat.

Also provided are an attitude control subsystem arranged, in this case, to direct the body of the satellite towards the Earth and the solar cells towards the sun as described in our earlier application No. GB 2320232; and a telemetry and command system by which the satellite transmits data concerning its operating conditions and receives commands from a satellite control centre causing it to, for example, adjust its position in orbit.

The bus may be, for example, the HS601 or HS601 high power satellites. or the HS702 satellite, all available from Hughes Space and Communications Company, in California, US.

Satellite Payload

Each satellite payload generates a plurality of spatially separated user link radio frequency beams, B1-BN in a manner described in more detail below. Each satellite also has an array of radiation reception directions which intercept

the surface of the Earth; the reception directions roughly coincide with the beams. The directions of the beams are at defined stereo angles with the antenna centre axis or "boresight", which (in this embodiment) is directed vertically towards the centre of the Earth. Each beam is directed towards a respective user terminal. Thus, as shown in Figure 4, the beams are unevenly distributed over the satellite footprint - i.e. the portion of the Earth visible from the satellite (or which has visibility of the satellite above some minimum elevation angle such as 10°).

Any beam which is not centred on the boresight axis will have a non-circular profile, derived as the intersection of the conical beam with the spherical surface of the Earth. The sizes and shapes of the beams therefore vary with their positions (i.e. the position of the beam centre, referred to here as the 'beam aim point') on Earth.

The satellite also generates global uplink and downlink beams (e.g. a beam covering the whole satellite footprint area of the Earth) for carrying signalling traffic for setting up and pulling down calls, and requesting changes to allocated channel capacity. These may be generated by the same array antennas or by additional antennas (not shown).

Figure 5 illustrates the beam profile in section. The gain falls away from a maximum value at the beam centre. Beyond some point (e.g. 1dB or 3dB down) the beam may be unsuitable for use; this therefore defines the "edge" of the beam. However, the beam continues to have an amplitude, and

thus to be capable of interfering with other co-channel users, beyond this "edge".

The satellite payload comprises at least one steerable high gain spot beam antenna 3 providing a feeder link for communicating with one or more fixed Earth stations 6 connected to telecommunications networks; a receive array antenna 1 for receiving the plurality of reception directions R1-RN; and a transmit array antenna 200 for generating the plurality of beams B1-BN. The antennas 1-3 are provided on the side of the satellite which is maintained facing the Earth.

The transmit and receive antennas each comprise two dimensional array antennas with, for example, a few hundred elements each.

A brief explanation of the access methods employed will now be given. The feeder link antenna 3 operates at a transmit frequency of 7 GHz and a receive frequency of 5 GHz. The receive array antenna operates at a frequency of 2 GHz and the transmit array antenna at a frequency of 2.2 GHz.

The bandwidth available for each channel is 4 KHz, which is adequate for speech. Time Division Multiple Access (TDMA) is employed, with 40mS frames. In the to-mobile direction, there are 36 timeslots in each repeating frame, on frequency subcarriers each of 150KHz bandwidth. In the from-mobile direction, there are 6 timeslots in each frame, on frequency subcarriers each of 25KHz bandwidth.

Conveniently, the frequencies allocated to different satellites are such that no two satellites whose footprints overlap (i.e. who can be seen simultaneously from any point on the ground) share any common frequencies. This is conveniently achieved by partitioning the available frequencies between the two planes of satellites (or, in general. N planes) and then. within each plane, re-using frequencies only on every alternate satellite (or, where levels of coverage higher than double coverage are provided by the constellation, on every Nth satellite).

Referring to Figure 6, the electrical arrangement provided within the satellite payload comprises a forward link, for communicating from an Earth station to a terminal, and a return link, for communicating from the terminal to the Earth station.

The forward link begins at the feeder link antenna 3, the signals from which are bandpass filtered by respective filters 206a-206d and amplified by respective low noise amplifiers 207a-207d. The amplified signals are combined and down-converted to an intermediate frequency (IF) by a combiner/IF downconverter circuit 208. This IF signal is digitised by an analogue to digital converters (ADCs) 210.

The digitised IF signals are each then frequency-demultiplexed into separate 150KHz frequency slots by a frequency demultiplexer 211.

Under the control of a digital control circuit 113, a routing network 212 routes each of the frequency slots to one of the input ports of a digital

beamformer 220, which generates a plurality of energising signals for energising respective radiating elements 200a-200M of the transmit array antenna 200.

The digital beamformer network comprises a Fast Fourier Transform processor, which accepts, from the digital control circuit 13, a set of control parameters for each of the frequency and time channels. The control parameters comprise:

- The amplitude for the user channel;
- The subcarrier frequency;
- The Doppler shift offset; and
- The angular direction of the beam.

The beamformer is arranged to synthesise beams each in the specified angular direction with respect to the antenna boresight, at the specified frequency, with the desired amplitude, by multiplying the signal by the subcarrier frequency (including Doppler offset) .

The energising signals are each converted to an analogue signal by a respective digital to analogue converter (DAC) 215a-215N, the outputs of which are up-converted to a beam frequency lying within a 30 MHz range in the 2.2 GHz band by an array of IF/S band converters, amplified by a bank of M RF power amplifiers 217a-217M. and bandpass filtered by a bank of filters 218a-218M, prior to being supplied to the respective radiating elements 200a-200M.

The components of the return link are, in general, the reverse of those in the forward link. A plurality P of receiving elements 118a-118P receive incoming radio signals in the 2 GHz band from user terminals 2 on the Earth. The signal from each element is filtered and amplified by respective filters 118a-118P and low noise amplifiers 117a-117P, down-converted to a 5 MHz IF signal by an array 106 of down converters, and digitised by a respective ADC 115a-115N and fed to the input ports of a digital beamformer 120.

The uplink beamformer 120 is arranged to apply the same direction control data as the downlink beamformer 220, and amplitude and frequency offset control data supplied from the digital control circuit 13 (in the latter case, the Doppler offset is the same, but the frequency channel is different).

The signals at each of the N output ports of the beamformer 120 comprise 25KHz frequency channels each carrying 40mS TDMA frames divided into 6 timeslots. They are routed, under control of the control circuit 13, through a switch 112 to a predetermined input (corresponding to a particular frequency) of a frequency multiplexer 111 generating 25 MHz output signals which are converted to analogue signals by a DAC 110. The analogue signals are up-converted into 7 GHz signals by an up converter and RF divider network 118.

Each RF signal is amplified by an RF power amplifier (e.g. a travelling wave tube or solid state amplifier device) 107a-107d; filtered by a bandpass

filter 106a-106d; and supplied to a feeder link antenna 3 for transmission to a respective Earth station.

Thus, the system shown will be seen to consist of a feeder link communication subsystem comprising the elements 3, and 106-109 and 206-209; a channel separation and combination subsystem comprising the elements 211-214 and 111-114; and a mobile link communication subsystem comprising the elements 215-218, 115-118, and antennas 100 and 200.

The digital control circuit 13 comprises a store 502 and a digital processor 504. The store 502 is shown in Figure 7, and comprises static store 502a and a dynamically updated store 502b, each of which has an entry for each beam. Each beam is associated with a user terminal 2, with which each entry is therefore also associated. Each entry in the static table 502a comprises fields storing: the beam number; data defining the position of the beam aim point on Earth; the channels used (defined as frequency subcarriers of the forward and reverse link channels for the user the timeslots of the forward and reverse link channels; and the power for the forward and reverse link channels for the user).

Each entry in the dynamic table 502b comprises the beam number; data defining the beam direction (relative to the antenna) and the Doppler shift to apply.

The digital processor 504 connected is to the store 502, and receives control data from the Earth Station 6. The control data specifies the user

terminal positions, and time and frequencies to be used for each, to be written to the store 502.

Referring to Figure 9, the database 48 of the Earth station node 6 in this embodiment, comprises, for each terminal 2, a field defining the terminal position on Earth (e.g. in latitude and longitude, or as a three dimensional position relative to the centre of the Earth), a beam aim point position (which will be discussed in greater detail below) in similar dimensional co-ordinates; a beam power level specifying the power transmitted towards the user terminal; a beam frequency field specifying the frequency of the beam transmitted to the terminal (for example by specifying the frequency channel used); and a time slot field specifying the time slot used for communication by the terminal.

Operation of Satellite 4

The satellite 4 payload performs, essentially, two processing loops; a first in which new beam control data is received from the Earth station 6, and a second in which beam directions and Doppler compensations are periodically re-estimated to maintain direction and frequency accuracy.

Accordingly, as shown in Figure 8, in a step 1002 the satellite 4 determines whether new user beam data is being received from the Earth station 6 (on a suitable control channel) and, if so, in step 1004, data is received and written to the store 502 in step 1006.

In step 1008, a first beam is selected from those listed in the store and in step 1010 it is determined whether the current beam is the last beam. If not, in step 1012, the processor 504 calculates the Doppler shift to the user terminal from the satellite, utilising the user terminal position data stored in the table 502a, and the current satellite position (calculated from the satellite orbital data, or from other sources such as a GPS receiver on the satellite) and the satellite orbital speed (which is calculated from its orbit and position).

The Doppler shift information is then stored in the store 502b.

Next, in step 1016, the direction in which the beam is to be pointed (from the satellite) is calculated by reading the beam aim point position data from the table 502a and using the satellite position data as calculated above. This too is written to the store 502b in step 1018.

On having processed the last beam (step 1010) in the table 502, the control circuit 504 amends the router 212, 112 to take account of any new beam assignments from the Earth station 4, and sends the Doppler offset, direction, and power control data to the beamforming network 220, 120. The process then returns to step 1002 to detect further uplinked beam data from the Earth station 6.

The beamformers 220, 120 are operative thereafter to synthesise transmission and reception beams with the designated power, direction and frequency, towards the user terminal, allowing data transmission to take the place in conventional fashion.

The process of Figure 8 needs to be repeated on each occasion when data is received from the Earth station 6, since the beam aim points on the ground may have changed.

It also needs to be repeated sufficiently frequently to track the movement of the satellite in orbit; in other words, sufficiently frequently that the movement of the satellite footprint on the ground (determined by satellite altitude) in-between successive executions of the process of Figure 8 is small compared to the width of the beams, so that the gain of the link to the user is essentially unchanged between repetitions.

Operation of Earth Station 6 in a First Embodiment

Referring to Figures 10 and 11 the beam allocation and control processes performed by the Earth station 6 will now be described.

When a new user wishes to make a call, or when call is to be placed to a user terminal 2 from a terrestrial terminal 12, after initial paging signalling, the user terminal position is derived in step 2002 for example, as described in GB 9919568.7.

In this embodiment, the database 48 includes a section 48a storing, for each user terminal record, a field indicating the beam aim point (in other words, the co-ordinates of the point on the Earth where the centre of the beam serving the user terminal falls); a field indicating the beam power (which is allocated in accordance with an adaptive power strategy as is well known in cellular and satellite communications systems, based on measurements of

signal quality); fields indicating the beam frequency (or frequencies) and timeslot (or timeslots), in other words, the channel used by the beam.

In step 2004 of Figure 10, the processor reviews the database 48, and selects those entries which have beam aim positions close to the user position of the new terminal to be allocated a beam. The processor then calculates whether the user position falls within each such beam, by calculating the beam periphery (i.e. 3dB contour) on the Earth, taking into account the satellite position. If the user uses the same frequency and time slot as an existing beam which it is within, there will be strong interference and the allocation of the same channel to the user therefore cannot be made.

Thus, in step 2006, all channels (i.e. frequency/timeslot pairs) not used in neighbouring and overlapping beams are selected for further processing.

Where two beams are centred within about two beam widths of each other, and use the same frequency and time slot, interference is inevitable since beams do not have abrupt edges. However, even where this criterion is not met, there may still be substantial interference, since the cumulative effect of several more distant beams may give a sufficiently high interference level to cause problems.

Accordingly, in step 2008, the processor reviews the database 48 for all other terminal records which use the same frequency and time slot.

In step 2010, the processor determines what the effect of the other channels cumulatively would be on the new terminal, and what the effect of

allocating a channel to the new terminal would be on the other channel users. This is achieved by calculating the amplitude (or power), for each of the co-channel beams, at each of the user terminal locations, and summing all such beam amplitudes at each user terminal location. The calculation makes use of:

- the power allocated to each beam
- the gain of each beam at each user terminal location, based on
    - the user terminal position, and
    - the satellite position in orbit.

If the sum at each user terminal location is below a predetermined threshold, in step 2010, then in step 2012, the new frequency and time slot are allocated to the new user terminal in the table 45, and signalled to the new user terminal on a signalling channel in step 2013.

If, in step 2010, the new terminal or one of the existing terminals is found to have an interference level in excess of its threshold, referring to Figure 11, an attempt is made to resolve this by displacing the aim point of the new beam away from the location of the new user terminal.

Accordingly, in step 2042, the aim point is displaced randomly from the user terminal location by a small increment, and in step 2044, it is calculated whether the gain of the beam when centred on the new position would be satisfactory at the user terminal position.

The processor is arranged to calculate the gain of the beam at the user terminal position by taking into account the beam shape (i.e. gain profile) and the distance from the beam centre of the user terminal position. In this embodiment, the processor tests whether the gain is in excess of 0.5 dB down from that of the beam centre.

In step 2046, the process of calculating the levels of co-channel interference at each user terminal (discussed above) is repeated and it is determined, in step 2048, whether the highest levels of interference at user terminals have increased or decreased.

If (step 2048) all have decreased, then the processor returns to step 2042 and executes a further displacement of the beam aim point in the same direction. If some interference levels already in excess of the acceptable threshold are rising, then in step 2050 the processor selects a different direction for displacement and then returns to step 2042.

When (step 2048) the levels of interference are neither rising or falling, the beam aim point search has reached a local minimum of interference or, alternatively, a compromise between interference and loss of gain.

Accordingly, in step 2052, it is determined whether all interference levels now meet the threshold and, if so, the processor returns to step 2012.

Thus, in this way, the beam aim points (i.e. positions on Earth of the beam centres) can be de-pointed, away from the user terminals to which they

are directed, provided that the user terminals still fall within a central region of the beam guaranteeing reasonable communications link margin, to find either a local minimum of interference or an acceptable trade-off between gain and interference level.

By comparing Figure 12 with Figure 4, the effect of steering the beams apart will be apparent: the interference between neighbouring beams is substantially reduced whilst each beam continues to cover the user terminal point as shown in Figure 12, rather than being centred on the user terminal position as in Figure 4.

In a preferred form of this embodiment, as shown in Figure 9, for each user terminal (or, where the user terminal is using more than one channel, for each channel used by each user terminal) a current total of interference level is stored, representing the co-channel interference expected at that user terminal position on the or each channel used by the user terminal.

Thus, when a new channel is added, it is merely necessary to calculate the additional power of the new beam at the position of each user terminal sharing the same channel, and add this to the stored power level at each user terminal, to assess the effect of adding the new channel, rather than re-calculating the power of each beam at each user terminal sharing the same channel.

Thus, according to the first embodiment, an initial search of the available channels is made to exclude those channels already used by beams which substantially overlapped the new user terminal.

This procedure may be advantageous where the number of channels is relatively small, and the user terminals are densely spaced so that very large numbers of beams overlap; in each case, it is possible for a substantial fraction of the available channels to be exhausted in the vicinity of a user terminal, and so the above described procedure reduces the number of channels to be considered further efficiently and hence improves the allocation speed.

Operation of Earth Station 6 in a Second Embodiment

Under circumstances where the users are more evenly distributed through the satellite footprint, the second embodiment of the invention to be described results in more efficient allocation by omitting the above described initial step. Instead, available channels are ranked in order of their current utilisation, weighted in accordance with the positions of the beam aim points, to provide some measure of the average level interference likely to be experienced on each channel. Channels are then allocated to new users on the basis of the lowest level of utilisation (and hence average interference).

Accordingly, as shown in Figure 14, the database 48 includes a store 48b maintaining, for each channel (i.e. frequency/timeslot combination), an interference level field.

Referring to Figure 13a. on a new request for channel allocation. in step 3002. the processor reviews the interference level data stored in the store 48b and selects the channel with the lowest interference level in step 3004. In step 3006. using the contents of the store 48a described in relation to Figure 9. the processor calculates the level of co-channel interference at each of the user terminal positions using the channel in question and. if in step 3008. it is determined that the interference at each user terminal position is below an acceptance threshold then. (shown as step 3010) the frequency is allocated to the requesting user terminal.

If not, then in step 3012. it is determined whether the channel is the last in the list and. if not, the channel from the store 48b is selected which has the next lowest interference level in step 3014 and the process of Figure 3006 is repeated until the last channel is reached (step 3012) or an acceptable channel is located.

If no acceptable channel is found. then. referred to Figure 13b. in step 3016. the channel is selected which produced. at step 3006. the lowest levels of co-channel interference. Then in step 3018. the beam de-pointing process described above in relation to Figure 11 is repeated. to locate a set of beam aim points which result in a local minimum of interference.

In step 3022 it is re-determined whether the interference levels thus produced fall under the threshold and. if so, the channel is used (shown as step 3024). If not, and if further channels remain (step 3028). then in step 3026.

the channel which gave the next lowest levels of co-channel interference in step 3006 is selected and the process of step 3020 is repeated. If no suitable channel can be found then no channel allocation is made after step 3028.

After new allocation of a channel, the levels of interference stored in the store 48b are updated. The levels are calculated as follows:

For each channel. the power levels of all beams using that channel are each multiplied by a function of the distance of the beam aim point from the sub-satellite point (i.e. the centre of the area of visibility of the satellite on Earth).

The function decreases with increasing distance from the sub-satellite point and may tamper, for example, from a value of unity at the sub-satellite point to a value of 0.4 at the edge of the satellite footprint.

Summing together the powers of the beams using each channel gives an indication of the average level of the channel across the footprint of the satellite, and hence. of the level of co-channel interference.

Applying the position-dependent factor takes account of the facts that, for each beam which crosses the edge of the satellite footprint, part of the beam power cannot interfere within the footprint; and that the further towards the edge of the satellite footprint a beam lies, the less likely it is to have neighbours to interfere with. Thus, ranking channels by the magnitude of the interference factor thus calculated gives, to a first approximation, the likely

level of interference on a given channel and therefore represents a suitable ordering for testing channels to be allocated.

Although not shown in the above flow diagrams, it will be clear that in this embodiment and the first embodiment, resources may be allocated not only on initiation of a new call, but also during a call session, if a user wishes to switch for example from a voice communication requiring only a single channel to a high bandwidth data communication requiring multiple channels.

Likewise, user position data may be stored for a number of users to whom no communications channels are currently allocated, but who remain periodically and signalling contact with the Earth station node 6. In such cases, it is not necessary to initially determine position since this will already be known.

Equally, although not shown in the above flow diagrams, a user terminal may release channel resources where a call terminated, or drops from a high bandwidth to a lower bandwidth mode (e.g. data to voice). On the occurrence of this, the channels previously used are released and the interference levels maintained in the store 48b are re-calculated.

Summary of Embodiments

It will be seen that the present embodiments enable a more flexible distribution of the satellite power than hitherto with fixed beam arrays. Some or all of the beams may be concentrated onto "hotspot" concentrations of users, since beams are provided on demand to users rather than being

provided in a fixed array to all areas of the satellite footprint. At the same time, the heavy co-channel interference this could otherwise cause is mitigated by the re-use management methods described herein.

Providing the Doppler correction at the satellite enables the channel spacing on the feeder link to the Earth station node 6 to be reduced, since it is not necessary to provide for the possibility of Doppler correction within the feeder link; accordingly, the channels are closely multiplexed together in the feeder link on adjacent frequency bands without substantial frequency guard bands.

Since the satellite is calculating the Doppler compensation to be applied for each channel, it is also convenient for the satellite to calculate the beam directions as the satellite moves in orbit. Thus, it is only necessary for the Earth station node 6 to transmit beam aim points on Earth, on a relatively infrequent basis, rather than continually uplinking beam steering commands. This reduces the volume of signalling on the uplink control channels from the Earth station node 6.

In other respects, however, the satellite is able to act as a transparent transponder, repeating the signal from the feeder link on to the user terminal beams and vice versa without needing to demodulate the signals (which would require substantial on-board processing and could introduce additional signal delays).

Other Embodiments

It will be clear from the foregoing that the above described embodiment is merely one way of putting the invention into effect. Many other alternatives will be apparent to the skilled person and are within the scope of the present invention.

It will be apparent that the first and second embodiments could be used together. It will also be apparent that it would be possible simply to use the average power level ranking of the second embodiment as a tool for channel allocation, without further steps.

It would also be possible to use the allocation methods described in the first and second embodiments where a fixed grid of beams were provided, as an alternative to a rigid frequency re-use pattern.

Rather than performing an initial test for overlapping beams, it would be possible to calculate cumulative interference levels at each user terminal position from all beams at the outset.

Rather than de-pointing just the beam for the new user terminal to be added, it would equally be possible de-point existing beams which use the same channel, or to de-point both.

For certain beam shapes it might be possible to directly calculate a set of beam aim points which jointly achieved acceptable gains and minimise co-channel interference between a predetermined set of frequencies and time slots, rather than using an iterative approach as described.

Whilst single beams allocated to each user have been described, it would be possible (for example, where a large number of users are known to be at almost exactly the same position on Earth) to provide a single beam serving multiple users on a single or common frequency, allocating different time slots to each.

The numbers of satellites and satellite orbits indicated are purely exemplary. Smaller numbers of geostationary satellites, or satellites in higher altitude orbits, could be used; or larger numbers of low Earth orbit (LEO) satellites could be used. Equally, different numbers of satellites in intermediate orbits could be used.

Although TDMA has been mentioned as suitable access protocol, the present invention is fully applicable to other access protocols, such as code division multiple access (CDMA) in which a limited number of codes, or non-orthogonal codes are re-used or pure frequency division multiple access (FDMA).

Equally, whilst the principles of the present invention are envisaged above as being applied to satellite communication systems, the possibility of the extension of the invention to other communications systems (e.g. digital terrestrial cellular systems such as GSM) is not excluded.

It will be understood that components of embodiments of the invention may be located in different jurisdictions or in space. For the avoidance of doubt, the scope of the protection of the following claims

extends to any part of a telecommunications apparatus or system or any method performed by such a part, which contributes to the performance of the inventive concept.

Claims

1. A satellite system comprising at least one satellite (4); at least one Earth station (6), and a plurality of user terminals (2), the satellite (4) being arranged to provide a link between each user terminal (2) and the Earth station (6), via a plurality of user terminal link beams (B1-BN) carrying communications channels, there being fewer independent said channels than the maximum number of beams which said satellite (4) can generate, said channels being reused between said beams (B1-BN); the system comprising means for directing said beams to positions determined in dependence upon the positions of said user terminals (2), and means for allocating said channels to said beams to reduce co-channel interference between said beams at said user terminals (2).

2. A system according to claim 1, in which said directing means is arranged to determine said positions jointly in dependence upon the position of the or each user terminal to which it is directed, and in dependence upon the co-channel interference between that beam and others using the same channel.

3. A system according to claim 2, in which said directing means is arranged to determine said positions jointly in dependence upon:

- the position of the or each user terminal to which it is directed,
- the co-channel interference between that beam and others using the same channel; and
- the gain of the beam at the user terminal.

4. A system according to claim 1, in which a single said beam is provided for each said user terminal (2).

5. A system according to claim 1, comprising a plurality of said satellites covering a region of the Earth.

6. A system according to claim 5, in which said satellites form a non-geostationary constellation.

7. A system according to claim 6, in which said constellation provides global coverage.

8. A system according to any of claims 5 to 7, in which the or each satellite (4) comprises means for maintaining each said beam directed to a position on Earth as the satellite moves in orbit relative to the Earth.

9. A system according to any of claims 5 to 7, in which the or each satellite (4) comprises means for applying a Doppler shift correction to each said beam.

10. A system according to claim 1, in which said channels comprise different frequencies.

11. A system according to claim 1 or claim 10, in which said channels comprise different timeslots on a common frequency.

12. A system according to claim 11, in which the number of timeslots on a common frequency in channels to a user terminal differs from the number in channels from a user terminal.

13. A system according to any preceding claim, in which said user terminals (2) comprise handheld terminals.

14. A system according to any preceding claim, in which said user terminals (2) comprise terminals with omnidirectional antennas.

15. Channel allocation apparatus for use in the system of any preceding claim.

16. Apparatus according to claim 15, comprising:

- means for calculating interference level data for each said channel. and
- means for allocating channels in accordance with said interference level data.

17. Apparatus according to claim 15 or claim 16, said apparatus being provided at a said Earth station (6).

18. A satellite for use in the system of any of claims 1 to 14.

19. A user terminal for use in the system of any of claims 1 to 14.

20. A method of channel allocation of a plurality of satellite communications channels carried over beams of a multibeam satellite to user terminals, there being fewer independent said channels than the maximum number of beams which a said satellite can generate, said channels being reused between said beams; the method comprising;

- determining the existing level of co-channel interference on said channels between said beams, and

- allocating a new channel which has a low existing level of co-channel interference.

21. A method of channel allocation of a plurality of satellite communications channels carried over beams of a multibeam satellite to user terminals, there being fewer independent said channels than the maximum number of beams which a said satellite can generate, said channels being reused between said beams; the method comprising;

- determining, for each channel, the level of co-channel interference on other beams which would be produced by the additional use of that channel on a further beam: and
- allocating a new channel which has a low existing level of co-channel interference.

22. A method according to claim 20 or claim 21, in which the step of determining comprises utilising beam power data representing the transmitted power on each said beam.

23. A method according to any of claims 20 to 22, in which the step of determining comprises utilising position data representing the relative position of each said beam.

24. A method according to any of claims 20 to 23, in which said beams are individually steered to user terminal positions.

25. A method of satellite communications comprising;

- defining individual user beams from a satellite in non-geostationary orbit, one for each of a plurality of user terminals, so as to serve all user terminals through respective individual beams;
- allocating channels to said beams so as to minimise co-channel interference at said user terminals between beams using the same channel; and
- maintaining said beams pointing to positions related to those of said user terminals.

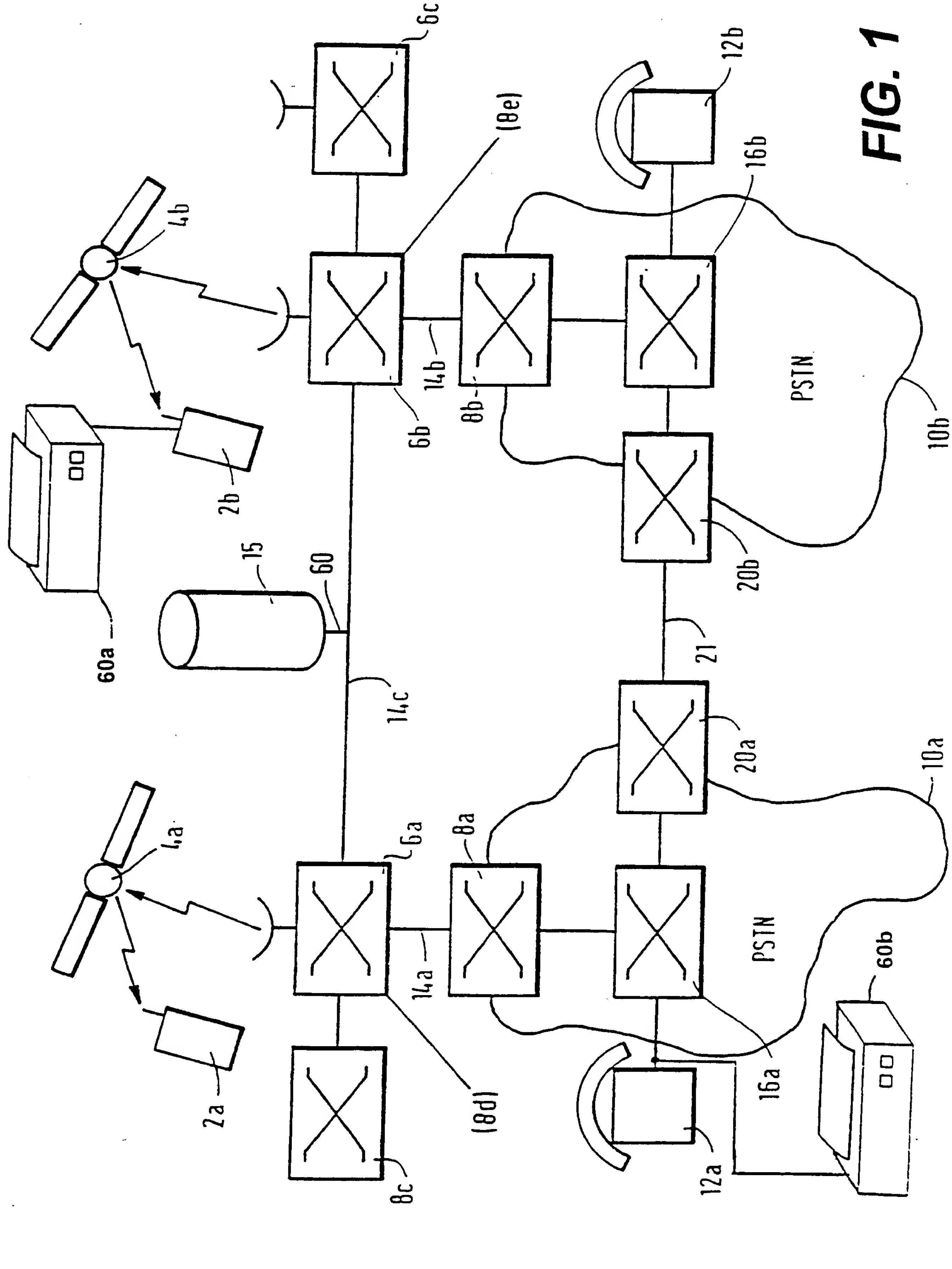

6c
12b
(8e)
4b
16b
14b
8b
6b
PSTN
10b
2b
15
60
20b
60a
21
14c
20a
10a
4a
6a
8a
PSTN
60b
14a
2a
(8d)
16a
12a
8c

FIG. 1

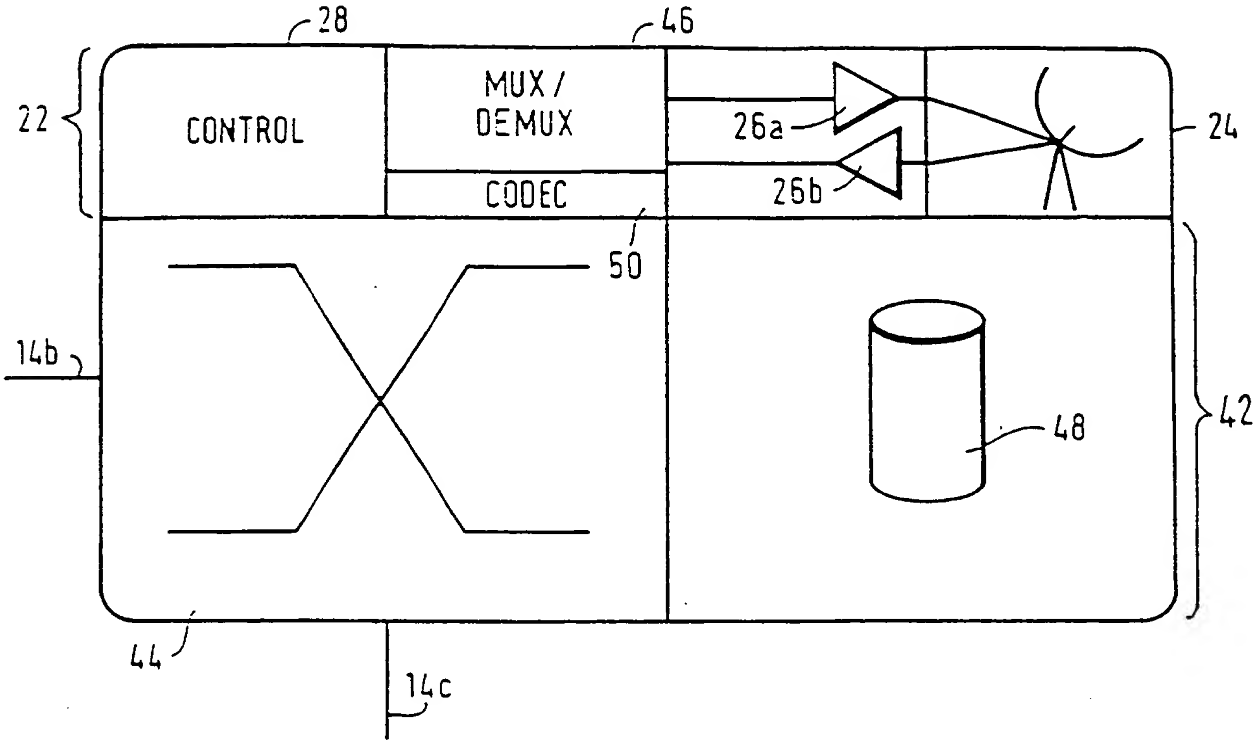

28
46
22
CONTROL
MUX / DEMUX
CODEC
26a
26b
24
50
14b
48
42
44
14c

FIG. 2

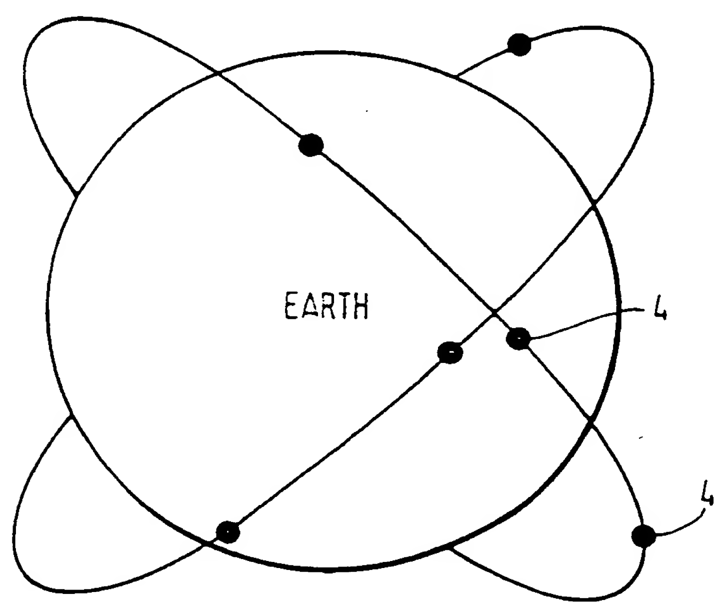

EARTH
4
4

FIG. 3

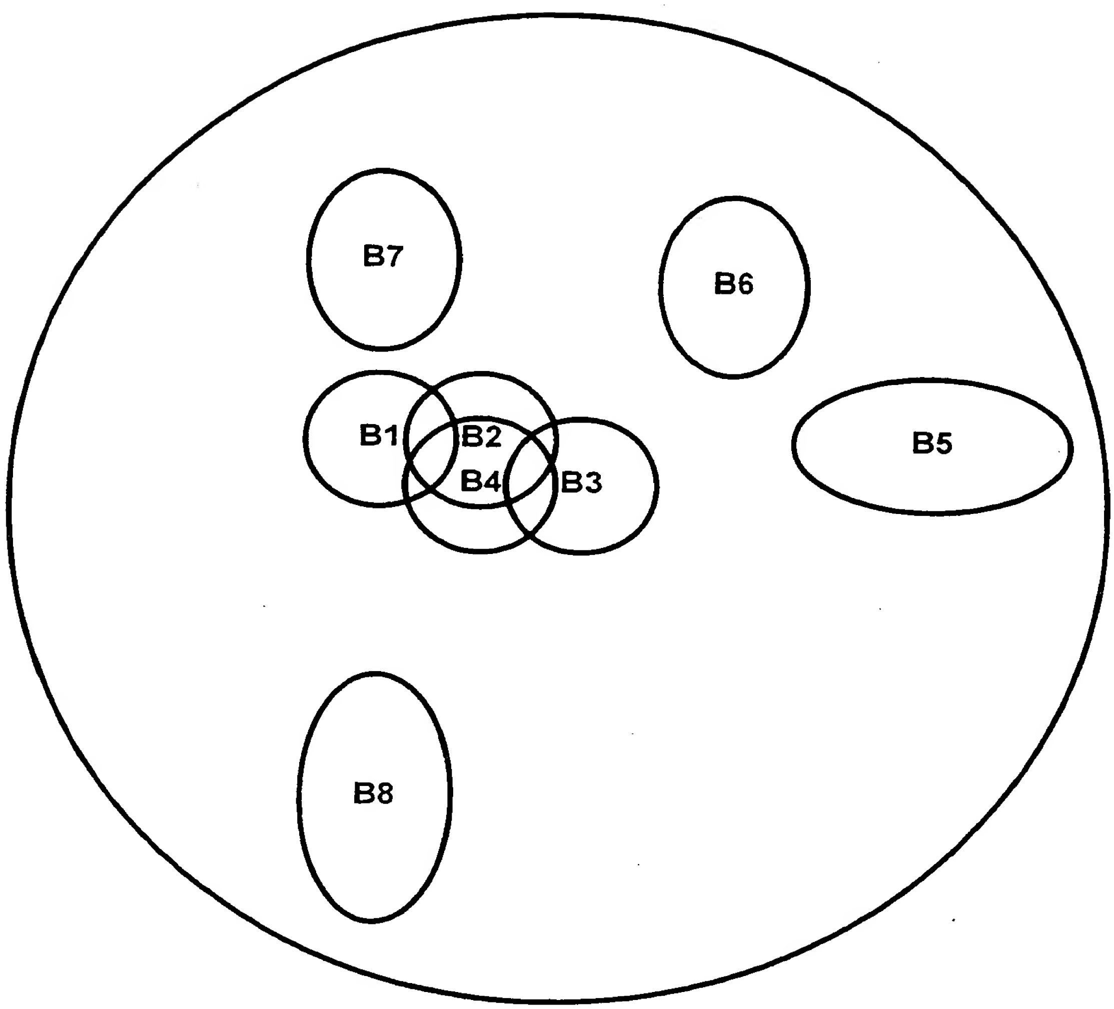


FIG. 4

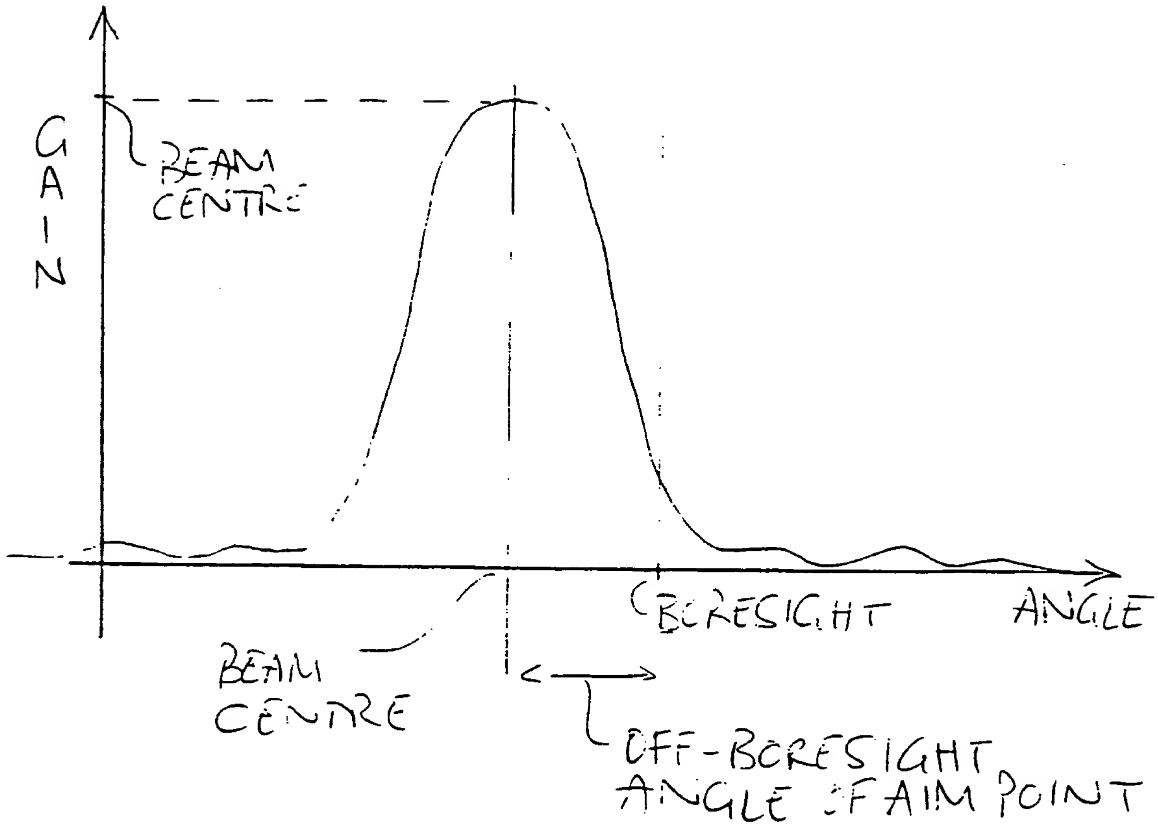


FIG. 5

502a

BEAM NUMBER	AIM POINT	POWER	CHANNEL(S)
1			
2			
N			

502b

BEAM NUMBER	DIRECTION	DOPPLER
1		
N		

FIG. 7

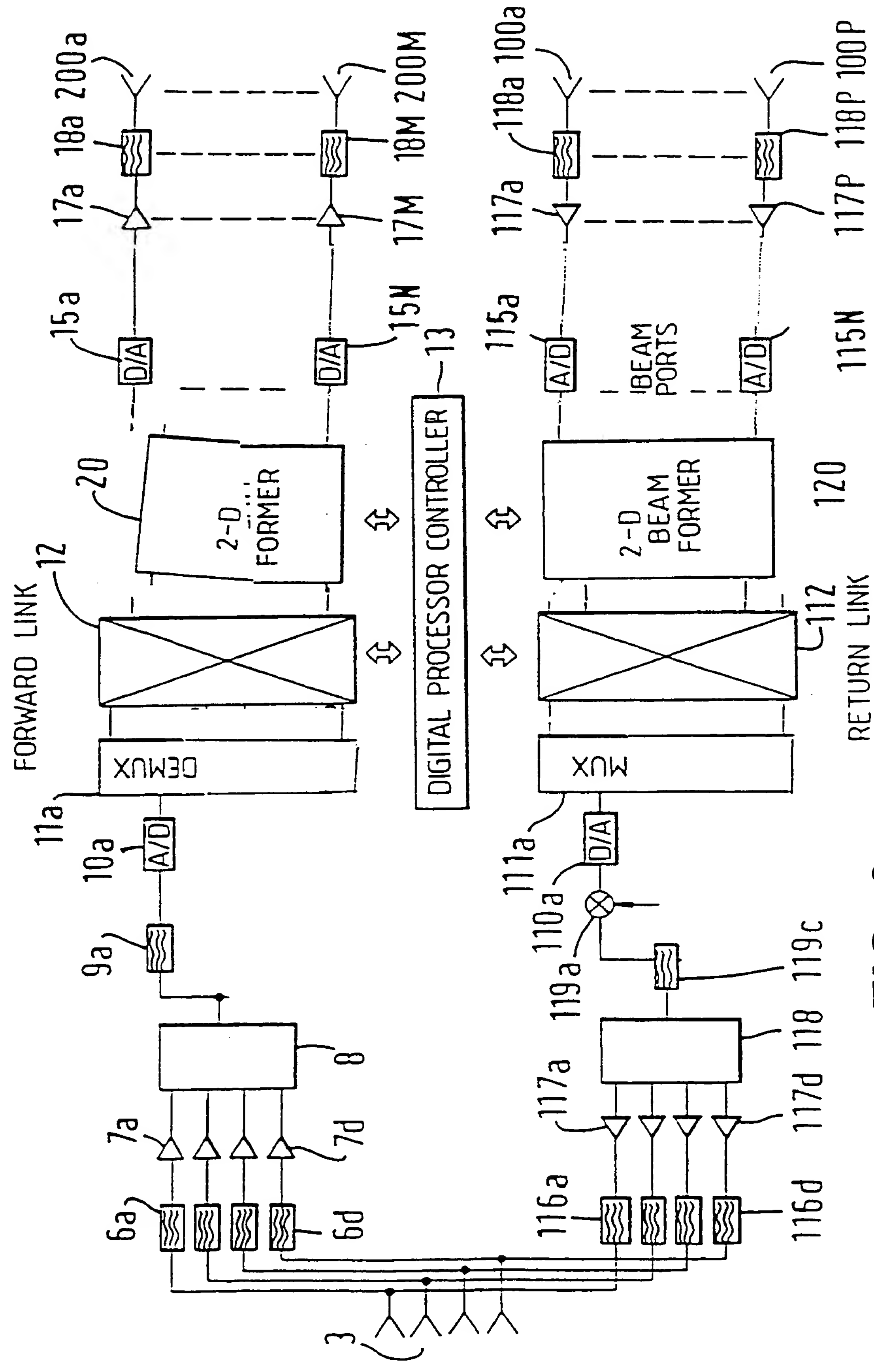

FORWARD LINK
RETURN LINK
DEMUX
MUX
2-D FORMER
2-D BEAM FORMER
DIGITAL PROCESSOR CONTROLLER
BEAM PORTS
A/D
D/A
3
6a
6d
7a
7d
8
9a
10a
11a
12
13
15a
15N
17a
17M
18a
18M
20
200a
200M
100a
100P
110a
111a
112
115a
115N
116a
116d
117a
117d
117P
118
118a
118P
119a
119c
120

FIG. 6

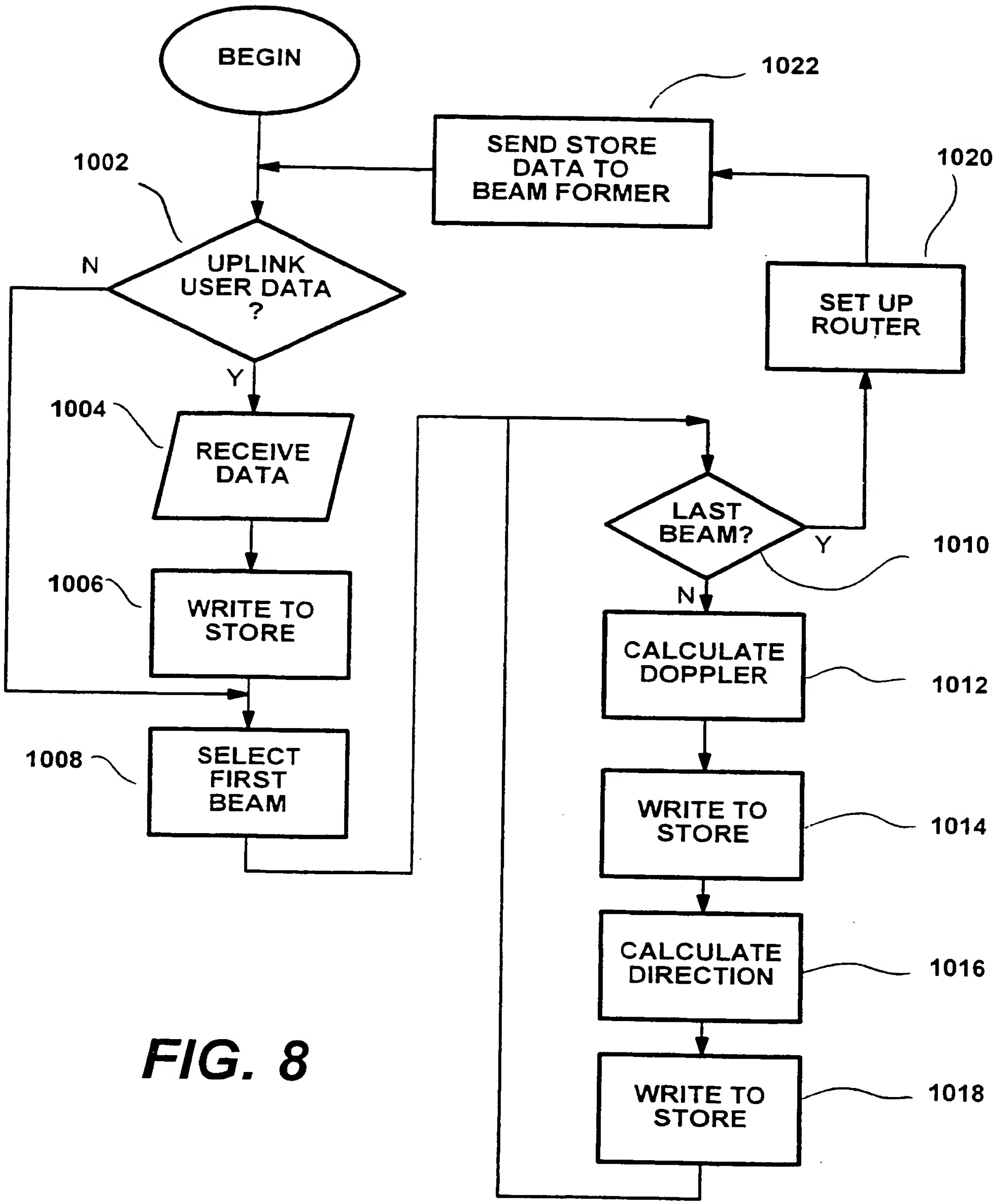

BEGIN
1002
UPLINK USER DATA ?
N
Y
1004
RECEIVE DATA
1006
WRITE TO STORE
1008
SELECT FIRST BEAM
1022
SEND STORE DATA TO BEAM FORMER
1020
SET UP ROUTER
LAST BEAM?
Y
N
1010
CALCULATE DOPPLER
1012
WRITE TO STORE
1014
CALCULATE DIRECTION
1016
WRITE TO STORE
1018

FIG. 8

48a

TERMINAL POSITION	BEAM AIM POINT	BEAM POWER	BEAM FREQUENCY	BEAM TIMESLOT	RESIDUAL INTERFERENCE

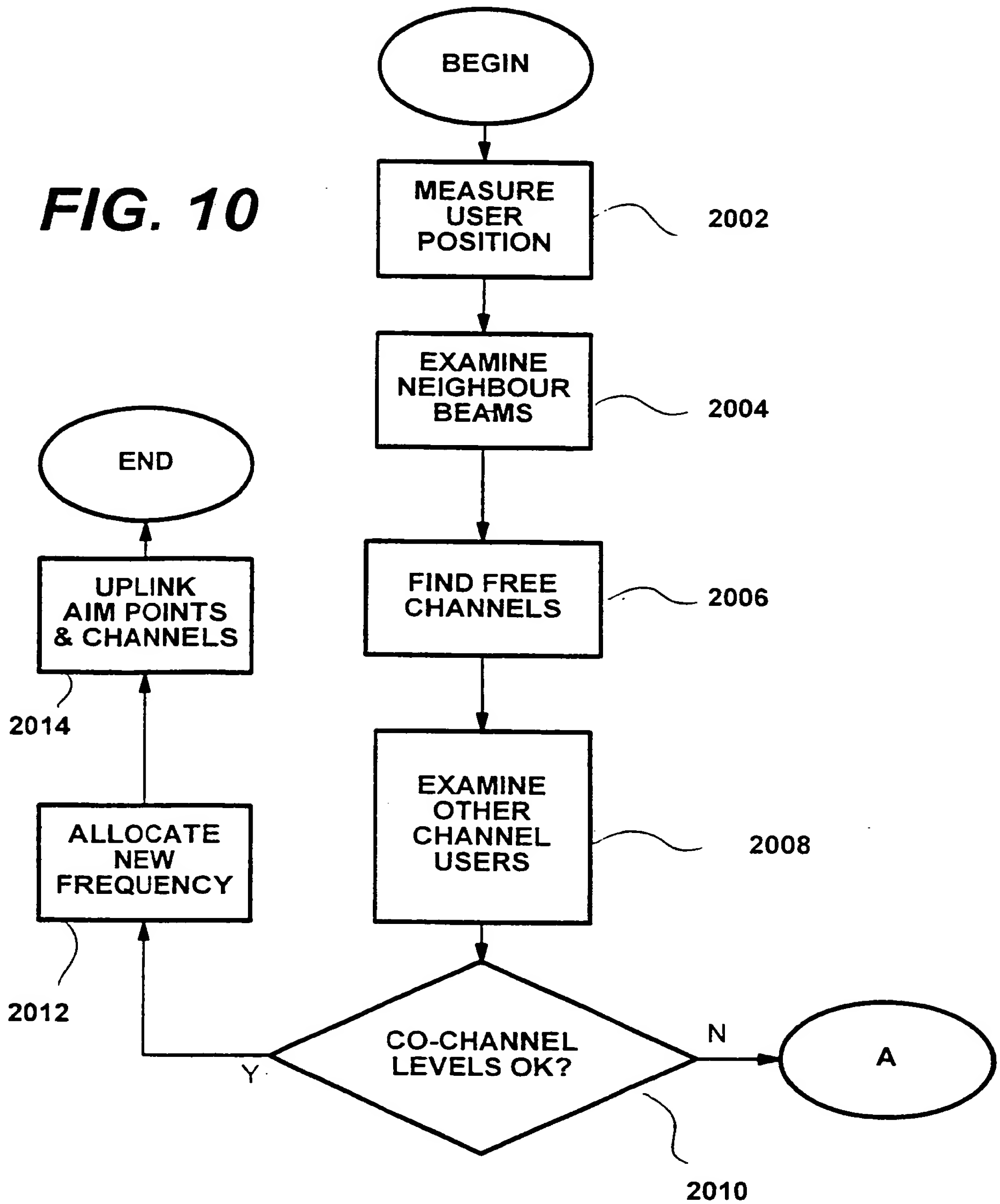
FIG. 9

48b

CHANNEL NUMBER	INTERFERENCE LEVEL
1	
2	
N	

FIG. 14

FIG. 10


BEGIN
MEASURE USER POSITION
2002
EXAMINE NEIGHBOUR BEAMS
2004
FIND FREE CHANNELS
2006
EXAMINE OTHER CHANNEL USERS
2008
CO-CHANNEL LEVELS OK?
2010
N
A
Y
ALLOCATE NEW FREQUENCY
2012
UPLINK AIM POINTS & CHANNELS
2014
END

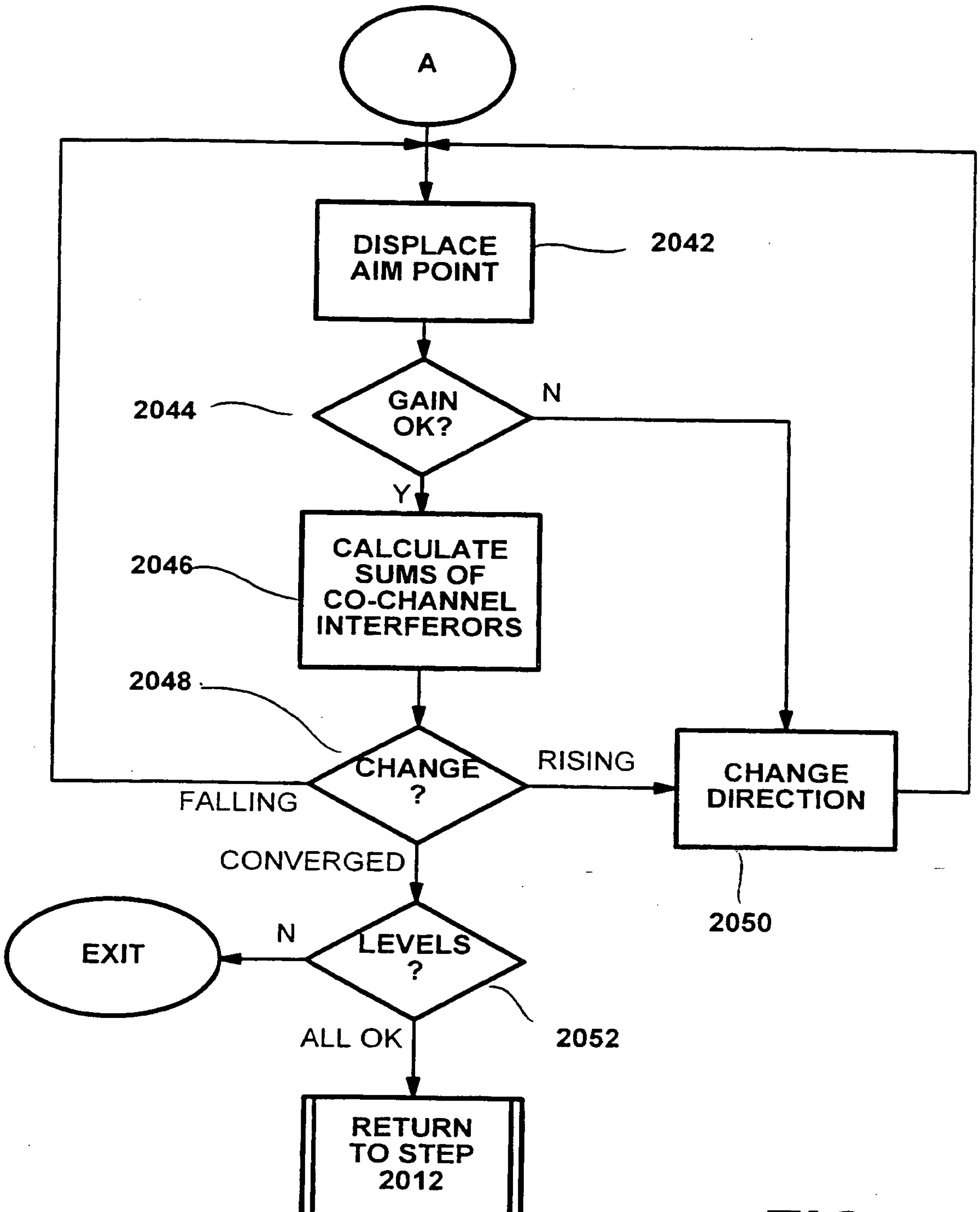

A
DISPLACE AIM POINT
2042
2044
GAIN OK?
N
Y
CALCULATE SUMS OF CO-CHANNEL INTERFERORS
2046
2048
CHANGE ?
RISING
FALLING
CHANGE DIRECTION
CONVERGED
2050
EXIT
N
LEVELS ?
ALL OK
2052
RETURN TO STEP 2012

FIG. 11

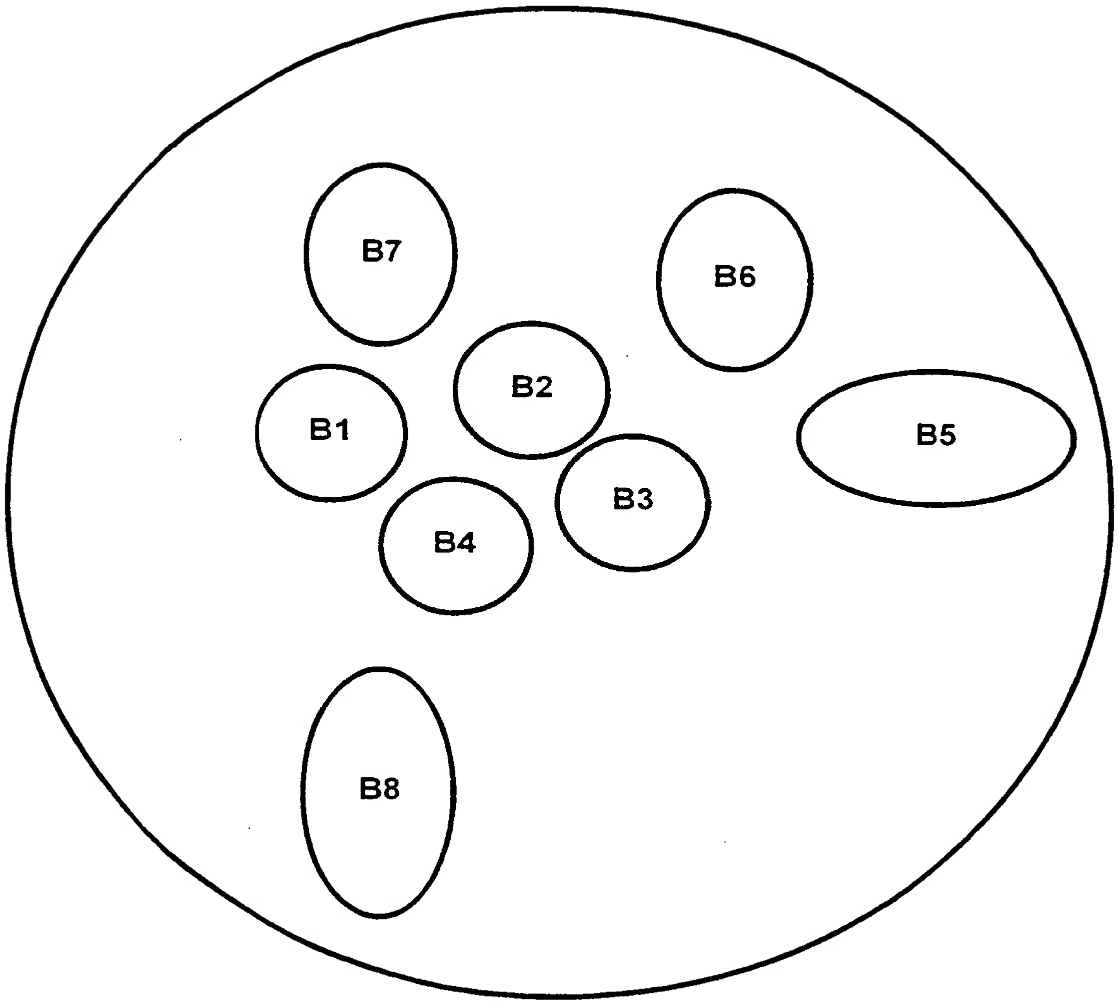


FIG. 12

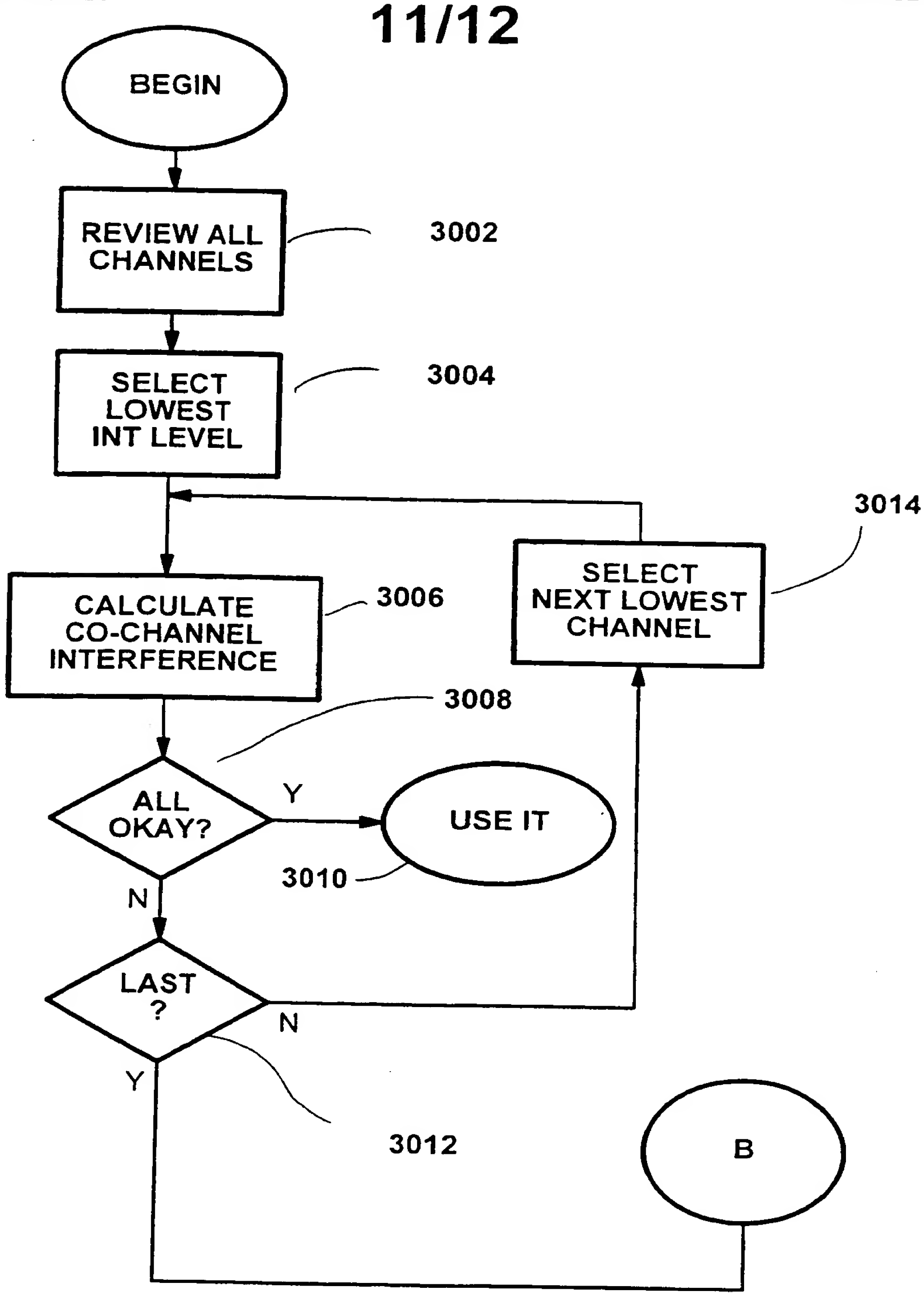
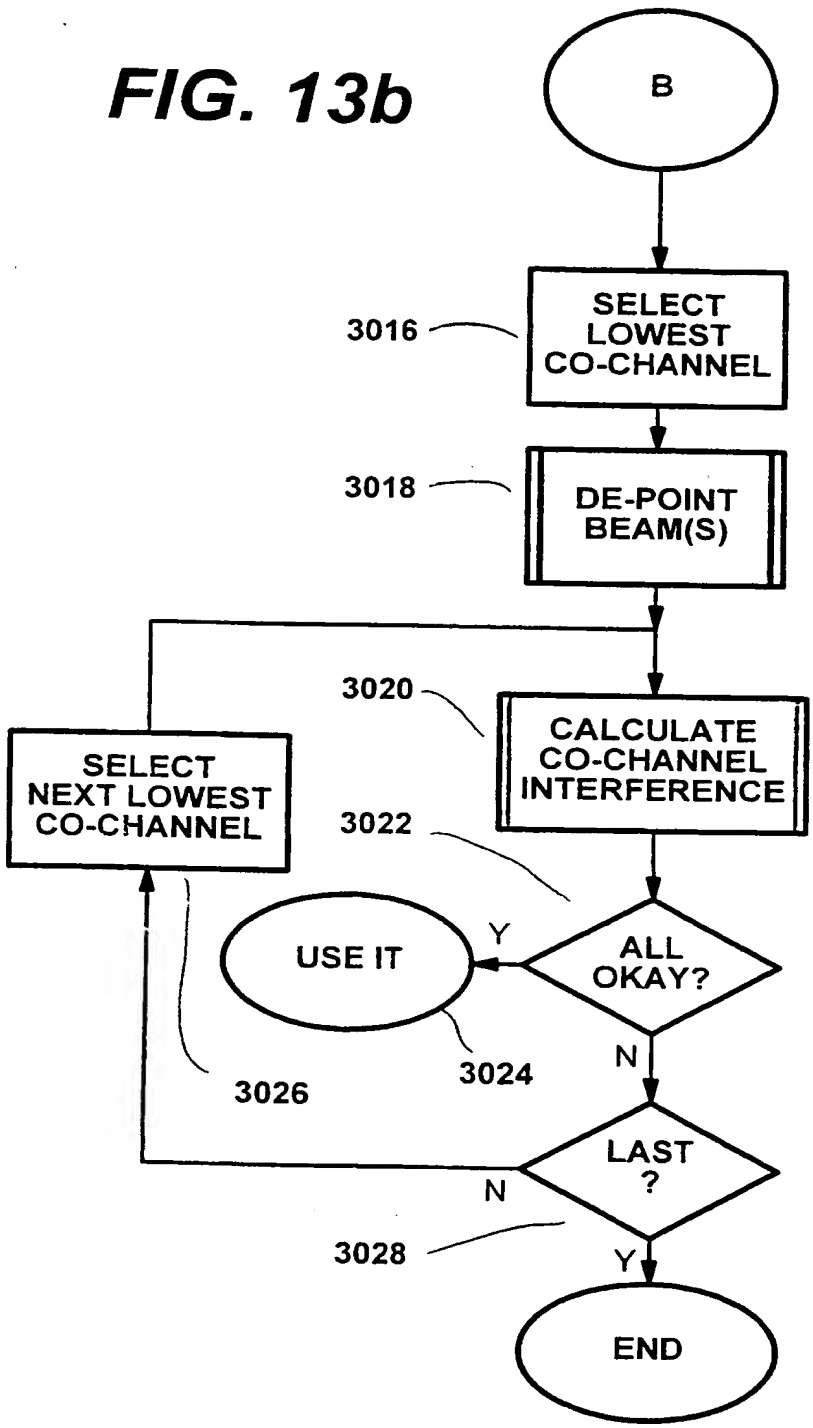

BEGIN
REVIEW ALL CHANNELS
3002
SELECT LOWEST INT LEVEL
3004
3014
SELECT NEXT LOWEST CHANNEL
CALCULATE CO-CHANNEL INTERFERENCE
3006
3008
ALL OKAY?
Y
USE IT
3010
N
LAST ?
N
Y
3012
B

FIG. 13a

FIG. 13b


B
3016
SELECT LOWEST CO-CHANNEL
3018
DE-POINT BEAM(S)
3020
CALCULATE CO-CHANNEL INTERFERENCE
SELECT NEXT LOWEST CO-CHANNEL
3022
ALL OKAY?
Y
USE IT
3024
N
3026
LAST ?
N
3028
Y
END

INTERNATIONAL SEARCH REPORT

Inte   onal Application No
PCT/GB 01/00790

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04B7/185 H04B7/204

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 305 578 A (MOTOROLA) 9 April 1997 (1997-04-09) page 4, line 10 -page 6, line 37 page 8, line 27 - line 36; figures 3,4 ---	1-25
X	GB 2 318 947 A (MOTOROLA) 6 May 1998 (1998-05-06) page 4, line 3 - line 13 page 6, line 14 - line 22 page 11, line 29 -page 12, line 25 ---	1-25
A	EP 0 749 217 A (ALCATEL) 18 December 1996 (1996-12-18) claims 1-29 --- -/--	1-25

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 April 2001	15/05/2001
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Bischof, J-L

1

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INTERNATIONAL SEARCH REPORT

Inte nal Application No
PCT/GB 01/00790

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 484 662 A (MESSERSCHMITT-BÖLKOW-BLOHM) 13 May 1992 (1992-05-13) claims 1-9 -----	1-25

1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte ›nal Application No
PCT/GB 01/00790

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
GB 2305578	A	09-04-1997	US	5612701	A	18-03-1997
			FR	2738980	A	21-03-1997
			IT	RM960611	A	09-03-1998
GB 2318947	A	06-05-1998	US	5754139	A	19-05-1998
			CA	2217805	A	30-04-1998
			DE	19747065	A	07-05-1998
			FR	2755329	A	30-04-1998
			JP	10145275	A	29-05-1998
EP 749217	A	18-12-1996	FR	2735303	A	13-12-1996
			FR	2735304	A	13-12-1996
			DE	69604618	D	18-11-1999
			DE	69604618	T	31-05-2000
			JP	9008722	A	10-01-1997
EP 0484662	A	13-05-1992	DE	4034979	A	07-05-1992